



# Mitigating Corrosion in Mg Sheet in Conjunction with a Sheet-Joining Method that Satisfies Structural Requirements within Subassemblies

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U.S. DEPARTMENT OF  
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National Laboratory  
Impact Initiative



**EMN** Energy  
Materials  
Network

Project ID # mat143

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# Overview

## Timeline

- › Start: October 2017
- › Finish: September 2019
- › % Complete ~45%

## Budget

- › Total project funding
  - DOE: \$ 300K
  - Industrial cost share: \$ 425K
- › Funding Since Inception: \$ 300K
- › Future Funds Anticipated: \$ 0

## Technology Gaps/Barriers

- › Lack of corrosion resistant magnesium (Mg) alloys
- › Lack of cost-effective, durable protective coatings
- › Limited availability of joining technologies and corrosion protection systems for Mg-X mixed material joints

## Partners

- › Tier-1 Supplier: Magna International - Stronach Centre for Innovation (SCFI)

# Relevance/Objective

- Use of multi-material solutions is going to be the trend for future vehicles in order to achieve the desired weight reduction
  - 155 kg body-in-white mass reduction in a Multi-Material Lightweight Vehicle Mach-II design relative to a 2013 Fusion baseline vehicle, where Class A exterior body panels are warm-formed Mg sheets
- Two major challenges related to the use of multi-material solutions: (1) **corrosion**; and (2) **joining**
- In Mg-alloys, need for improved corrosion mitigation is a prime requirement, especially when coupled with a dissimilar metal because of galvanic corrosion problem

# Relevance/Objective (cont.)

## ➤ Protective coatings

1. Henkel pre-treatment (HP)
2. Henkel pre-treatment + E-coat (HPEC)

## ➤ Joining techniques

1. Arplas resistance spot welding (RSW)
2. Clinch lock
3. Breakaway stem rivet

## ➤ Material systems

1. Mg AZ31/Mg AZ31
2. Mg AZ31/Aluminum (Al)
3. Mg AZ31/Steel

➤ Aim to determine influence of joining processes on the corrosion protection efficiency of the surface coatings.

➤ PNNL providing necessary testing and analysis support to industry partner



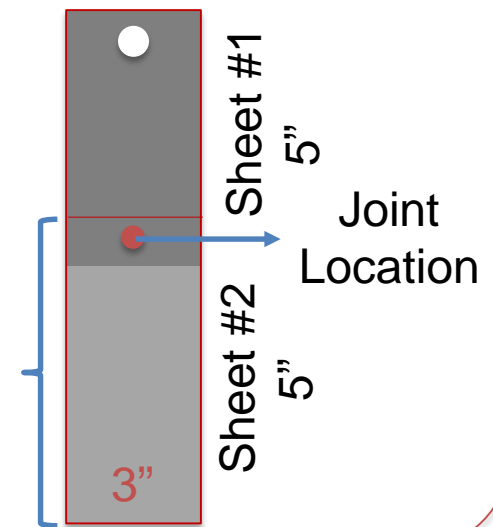
# Task/Milestone Summary

Year No.	Task/ Sub-task No.	Task Name	Duration (Months) (Start) (Finish)		Responsible Party	Current Status
1	M1	Determine Comprehensive Test Matrix and Design of Experiment	1	2	Magna	Completed
1	M2	Sample Preparation	2	6	Magna	
1	*P1	Baseline Characterization	1	9	PNNL	
1	*P1.1	Corrosion Testing	1	9	PNNL	
	*P1.2	Microstructural Characterization	1	9	PNNL	
1	*P1.3	Mechanical Property Characterization	1	9	PNNL	
1	M3	Sample Joint Assembly – Similar Alloys	6	12	Magna	Delayed Start (1 <sup>st</sup> shipment received March'19)
1-2	*P2	Similar Joints Characterization	7	18	PNNL	
1-2	*P2.1	Corrosion Testing	7	18	PNNL	
1-2	*P2.2	Microstructural Characterization	7	18	PNNL	To Start
1-2	*P2.3	Mechanical Property Characterization	7	18	PNNL	
1-2	M4	Sample Joint Assembly – Dissimilar Alloys	8	16	Magna	
2	*P3	Dissimilar Joints Characterization	13	24	PNNL	
2	*P3.1	Corrosion Testing	13	24	PNNL	
2	*P3.2	Microstructural Characterization	13	24	PNNL	
2	*P3.3	Mechanical Property Characterization	13	24	PNNL	
2	M5	Formulate Report	23	24	Magna	

# Approach

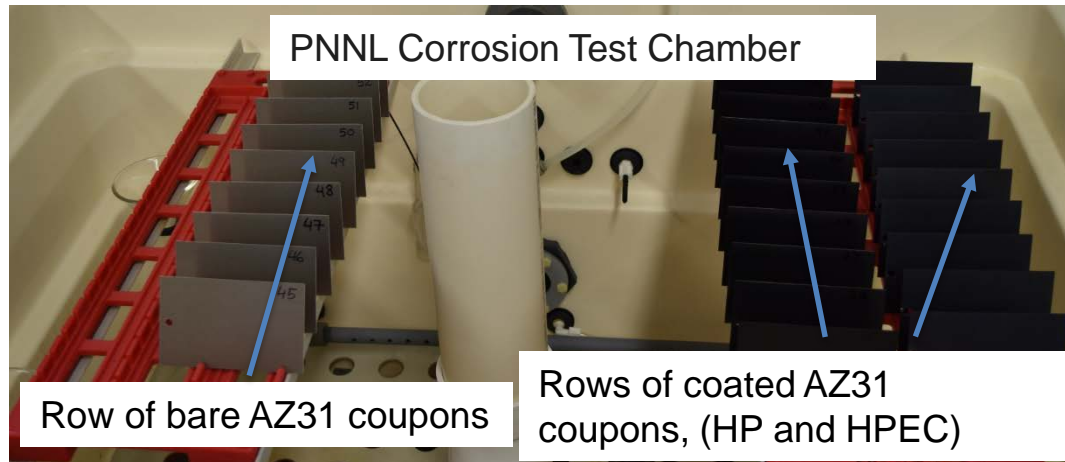
- Corrosion behavior of Mg-alloy AZ31
  - Bare AZ31
  - AZ31 + Henkel Pre-treatment (HP)
  - AZ31 + HP + E-coat (HPEC)
- Three types of joining technology being evaluated:
  - Arplas resistance spot welding
  - Breakaway stem rivet
  - Clinch lock
- Year 1: Baseline
- Year 2: All joint samples (AZ31/AZ31, AZ31/Al, AZ31/steel) evaluation
- Corrosion performance determined through ASTM B117 (salt spray) test

## Mg-X Corrosion Test Coupon



# Approach

- ASTM B117 test for 1500 hours (~2 months)
- Corrosion coupons (3" x 5") placed at an inclination on the testing trays



## ASTM B117 Test Conditions

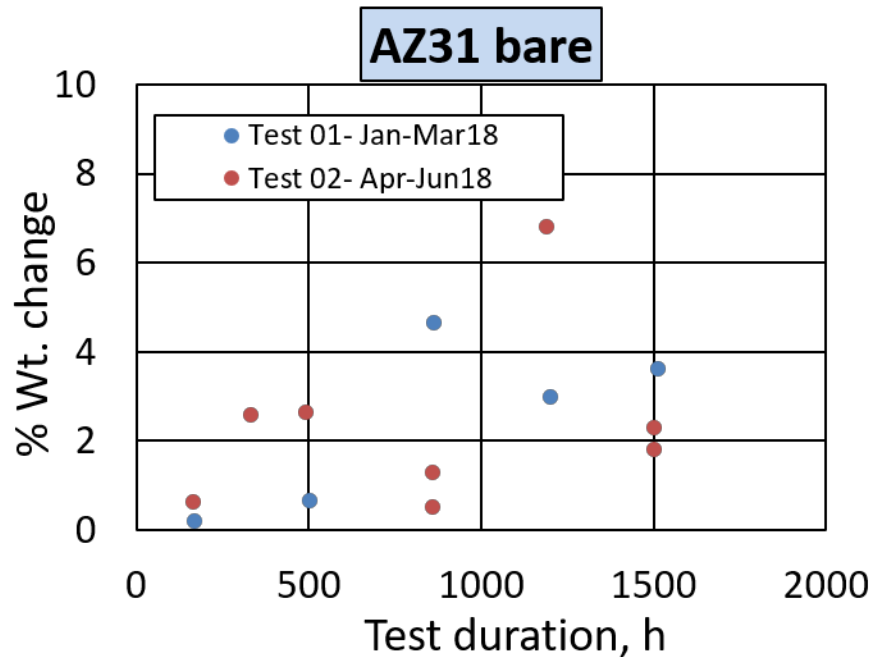
Test chamber temperature : 35° C  
5% sodium chloride solution  
pH of the solution: 6.5 – 7.2  
Fog collection rate: 1 – 2 ml/ hr  
Test duration : Up to 1500 hours

**Evaluate coating performance and mechanical integrity of the coating interface with base metal**

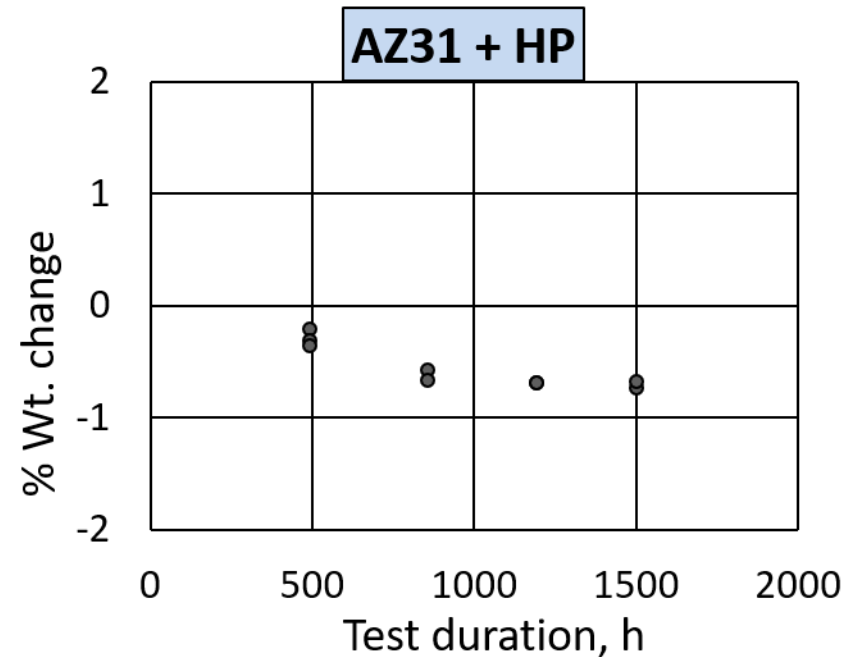
# Accomplishments

## %Wt. Change vs. Test Duration (ASTM B117)

*Corrosion coupons are taken out from the test chamber at a regular interval, dried, and weighed. % weight (wt.) change indicates the degree of corrosion*



Significant weight gain → heavy corrosion

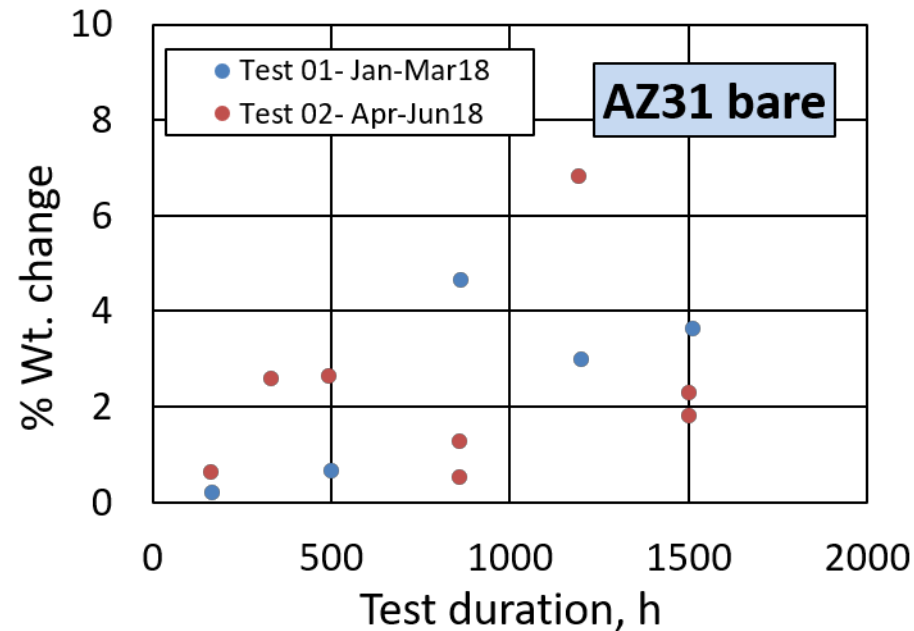
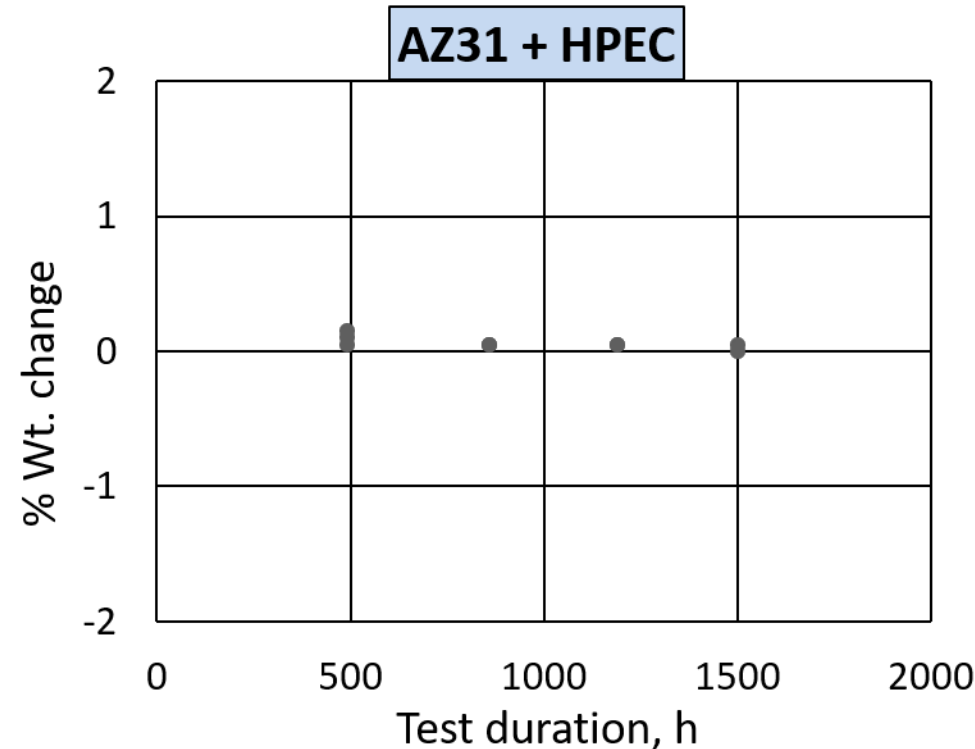


Slight loss of weight → Slow dissolution of the protective coating



## Accomplishments (contd.)

### %Wt. Change vs. Test Duration (ASTM B117 )



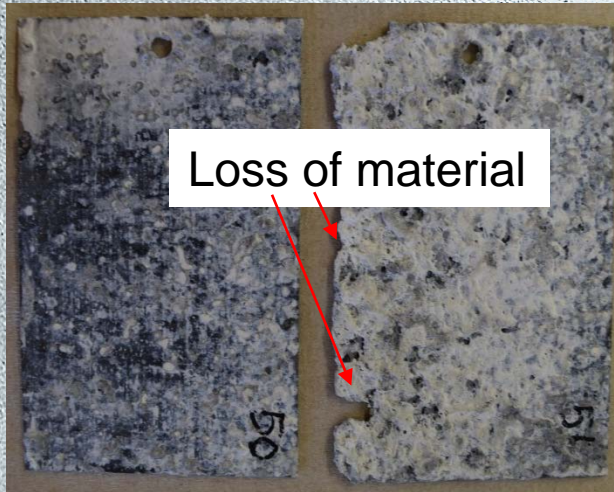
No change in weight over the test duration, indicating **best corrosion protection in AZ31 + HPEC sheets**



# Accomplishments

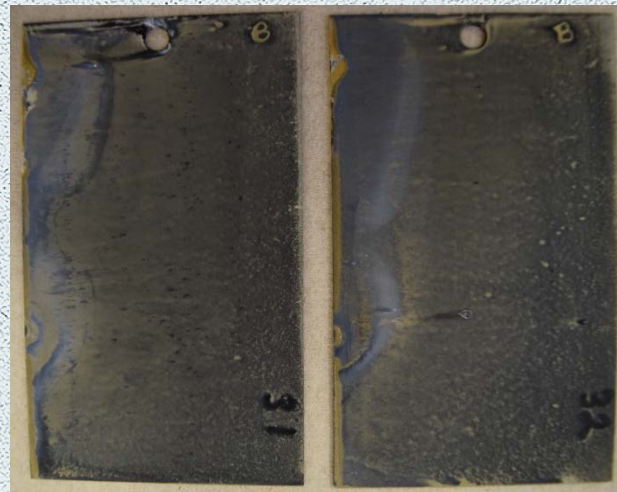
## Images of the corrosion test coupons after 1200 h of exposure

Bare AZ31



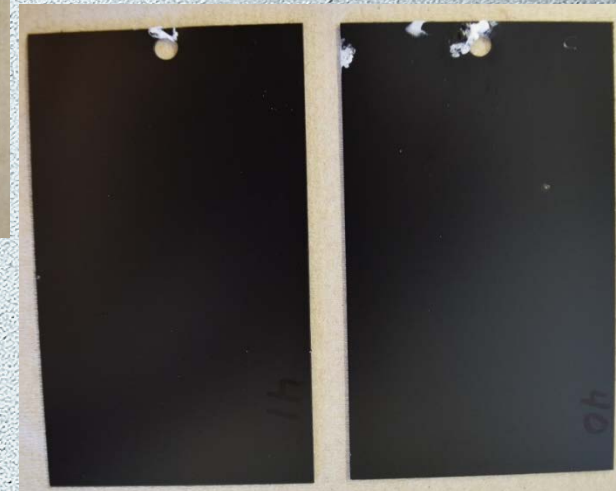
Significant corrosion

AZ31 + HP



Discoloration of the protective layer

AZ31 + HPEC



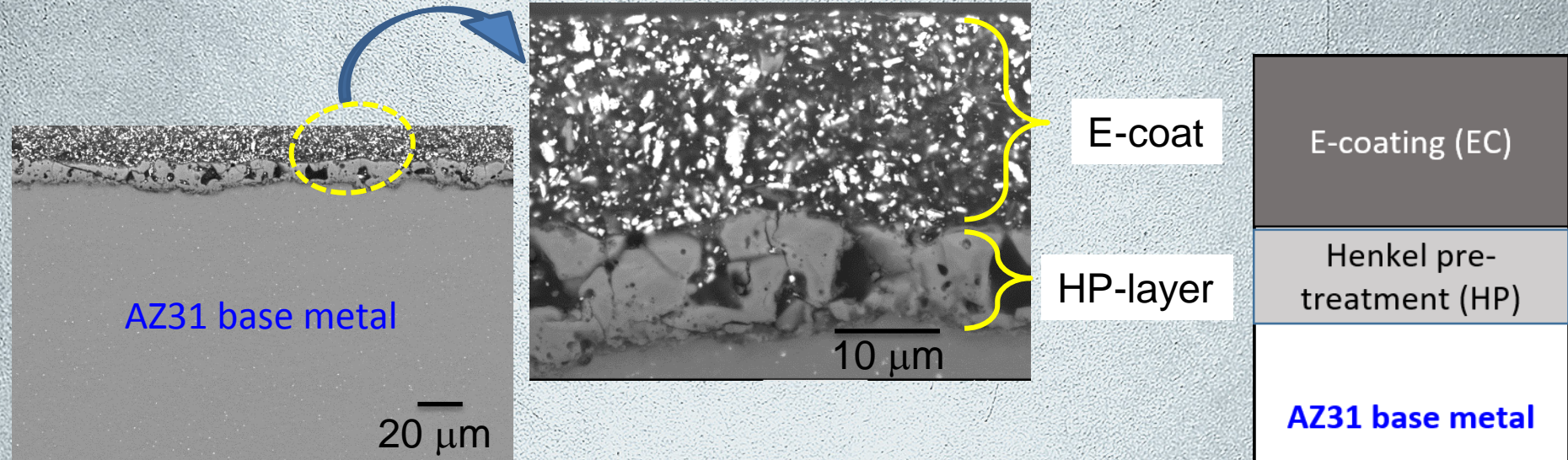
No apparent change in the protective layer

***Best corrosion protection is noted in HPEC coating***



# Accomplishments

Characterization of the AZ31 + HPEC coupons (SEM + EDS analysis), **t = 850 h**

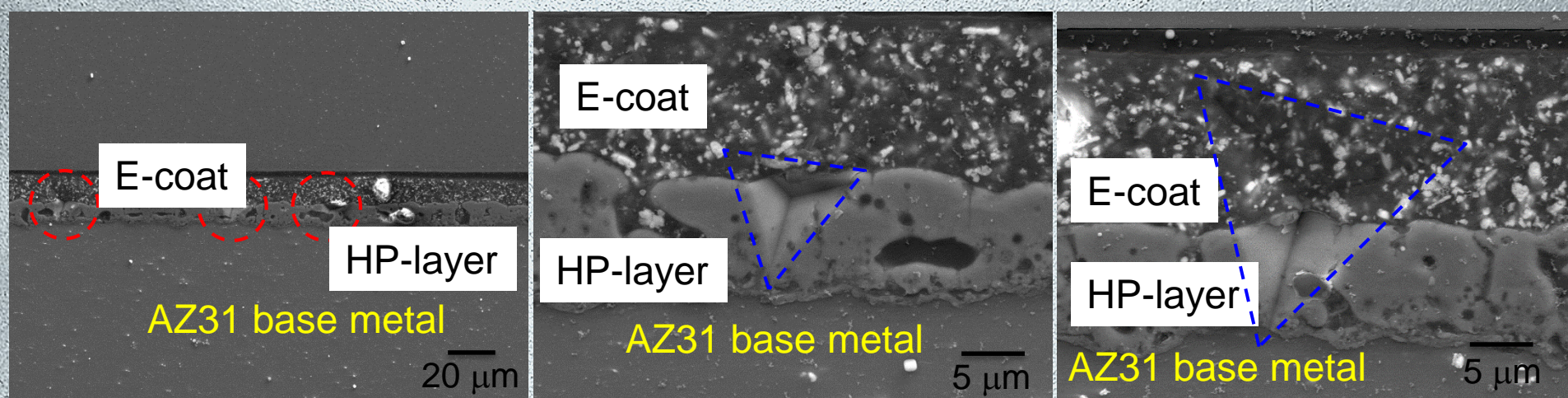


- **HP layer: Contains pre-existing pores**
- **E-Coat: No apparent change and remains dense even after 1500 h**



# Accomplishments

## Mechanical Integrity of HPEC



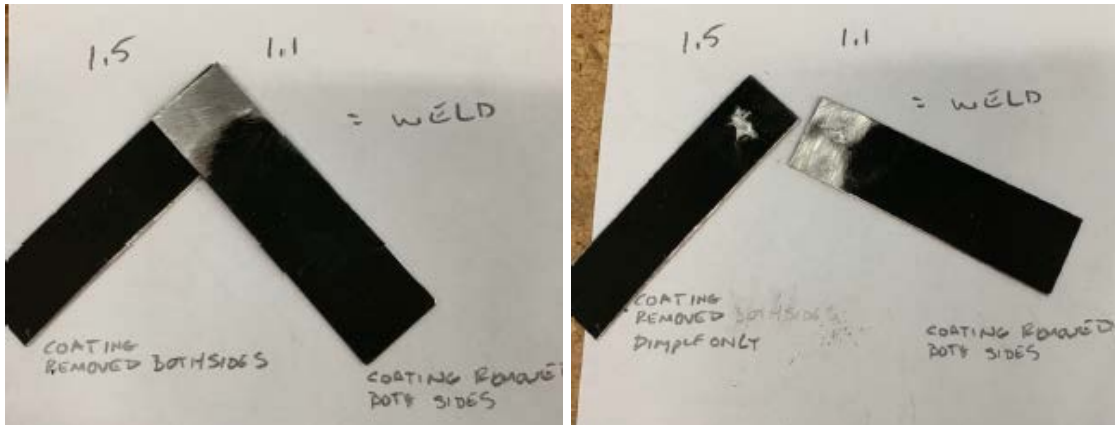
- The HP/EC interface appears to be stable, and does not delaminate under the application of point loads
- HP-layer contains numerous pores which get covered by the E-coating process
- E-coating provides a dense top layer to the underlying HP-layer
- Exposure of the base metal is thus stopped and improves corrosion performance.



# Accomplishments

## Joint Fabrication (at Magna)

ARPLAS RESISTANCE  
SPOT WELDING



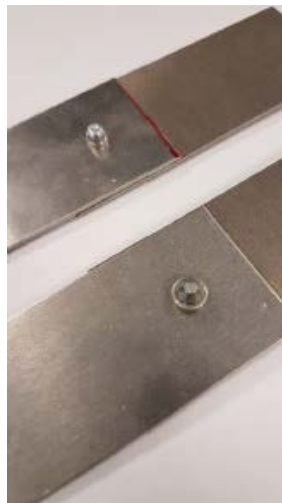
Successful Arplas welding only possible when pre-treatment layer (HP) is removed on both sides of each sheet metal coupon

1.5 mm thick AZ31 sheet being joined to 1.1 mm thick AZ31 sheet

BREAK AWAY  
STEM RIVETING



Rivet Head



Rivet Tail

- Both 3/16" and 1/4" all-Aluminum style rivets initially tested
- Closed-end 3/16" rivets chosen for further studies
- Advantage: Completely sealed rivet tail end prevents environmental/ chemical intrusion on tail end



# Responses to Previous Years Reviewers' Comments

## Comments

- “..how to make corrosion testing consistent..”
- How was PNNL's scope determined?
- “..what kinds of mitigating solutions is the project investing..”



## Response

- New sample holding fixture where samples will be hung vertically, therefore exposing both sides of the test coupon to salt fog equally
- This is a LightMAT project driven by industries' need to develop cost-effective, multi-material lightweighting solutions. Industry is using National lab capabilities and expertise to solve long-standing corrosion issues associated with the use of Mg
- Industry-provided joining methods, combinations of coatings etc. relevant to Mg alloys are being explored

# Collaboration and Coordination

- CRADA with Magna (industry-lead)
- Magna responsible for fabricating Mg/Mg, Mg/Al and Mg/steel joints
- Henkel providing corrosion protection solution to Magna

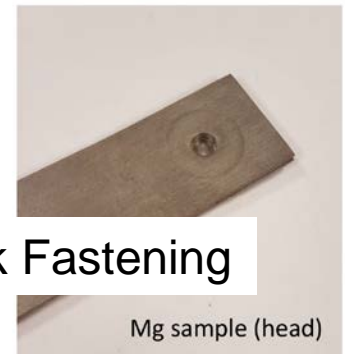
Arplas Resistance  
Spot Welding



Riveting



Clinch Lock Fastening



Examples of Mg-joints supplied  
by Magna

# Remaining Challenges and Barriers

- Project delays due to personnel and fabrication issues at industry partners. But those have been resolved and joint-samples are now being fabricated and tested at PNNL
  - First batch of Mg-joints (Mg/Mg) delivered in March 2019
- Uncertainty of coating integrity during joining process
- Uncertainty of coating affecting the joining process (e.g. as in Arplas RSW)
- Uncertainty if HP and EC are suitable for Al and steel

# Proposed Future Work

- Evaluation of similar joints (Mg/Mg)
  - Corrosion testing
  - Microstructural characterization and identification of potential sites that are prone to corrosion
- Evaluation of dissimilar joints (Mg-Al and Mg-steel)
  - Corrosion testing
  - Microstructural characterization

Any proposed future work is subject to change based on funding levels

# Summary

- Bare AZ31 shows severe corrosion during salt fog test → Significant weight gain due to  $\text{Mg}(\text{OH})_2$  formation
- Under corrosion conditions used (ASTM B117 test), both HP and HPEC offer good corrosion protection but HPEC appears better
  - As-coated HP layer is porous and not impervious to corrosion attack and showed some evidence of cracking at HP/AZ31 interface
  - As-coated E-coat layer is dense and remains dense during testing
- The HP/EC interface has strong integrity and does not delaminate under corrosion conditions used
- Compatibility between the joining method and coating schemes is being evaluated
  - Arplas resistance spot welding required the HP layer to be removed to expose base Mg on at least on both sides of the top sheet along with the mating side of the underlying bottom sheet of the work pieces





# Technical Backup Slides

Principal Investigator: **Aashish Rohatgi**  
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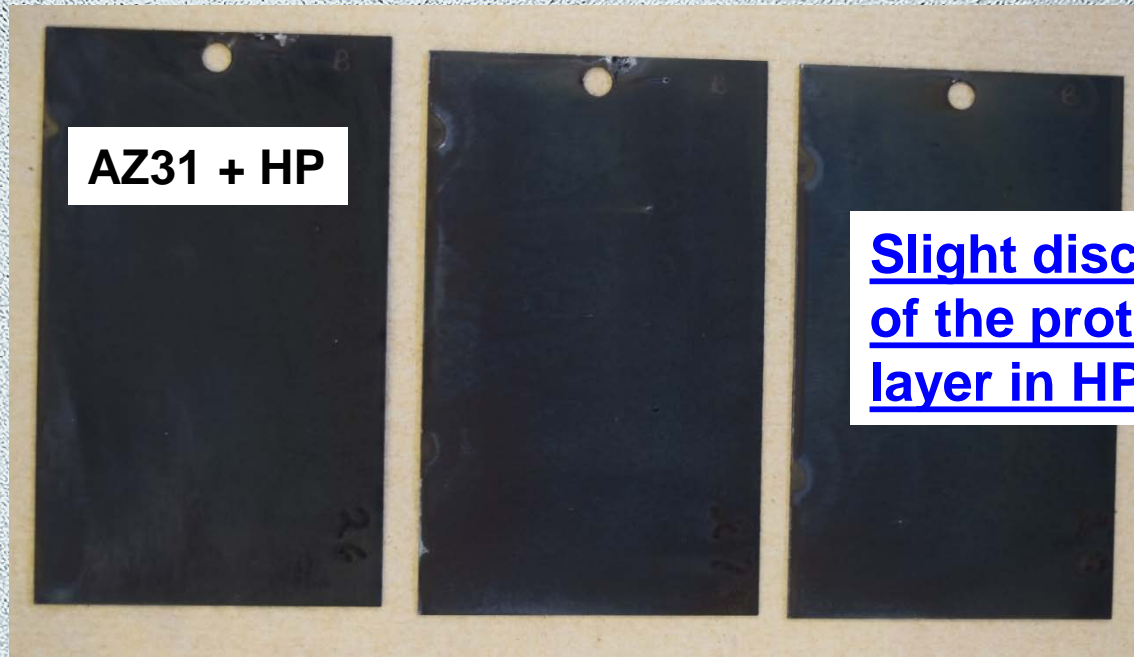


# Images of the corrosion test coupons after 500 h of exposure



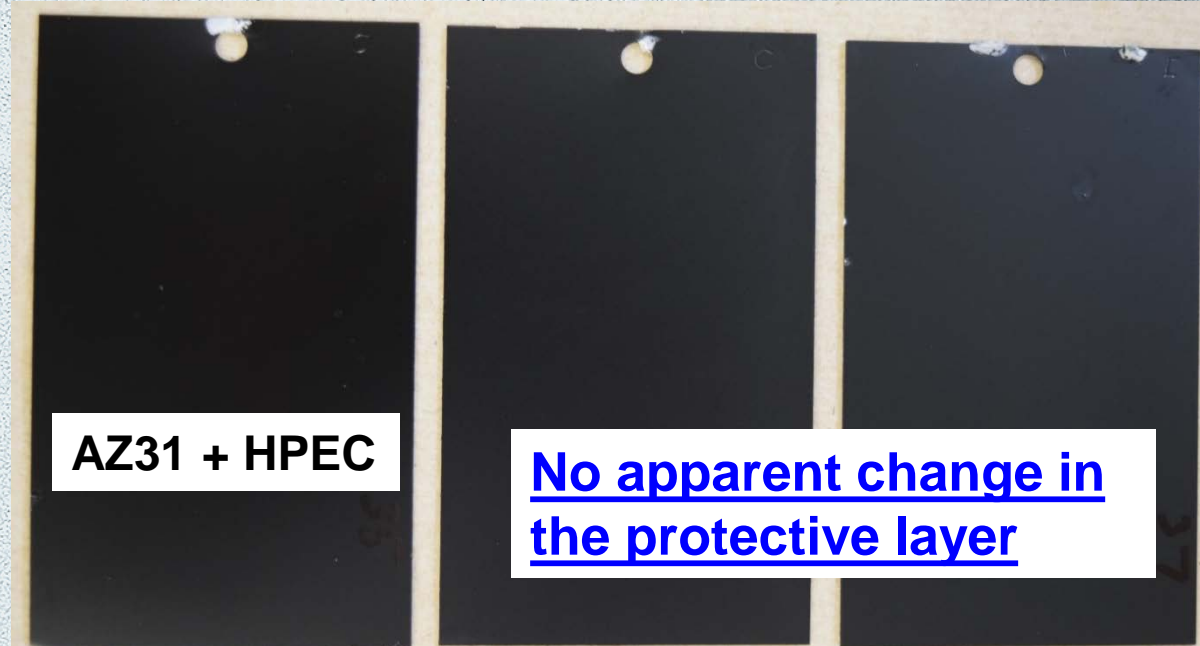
Bare AZ31

Significant corrosion



AZ31 + HP

Slight discoloration  
of the protective  
layer in HP samples

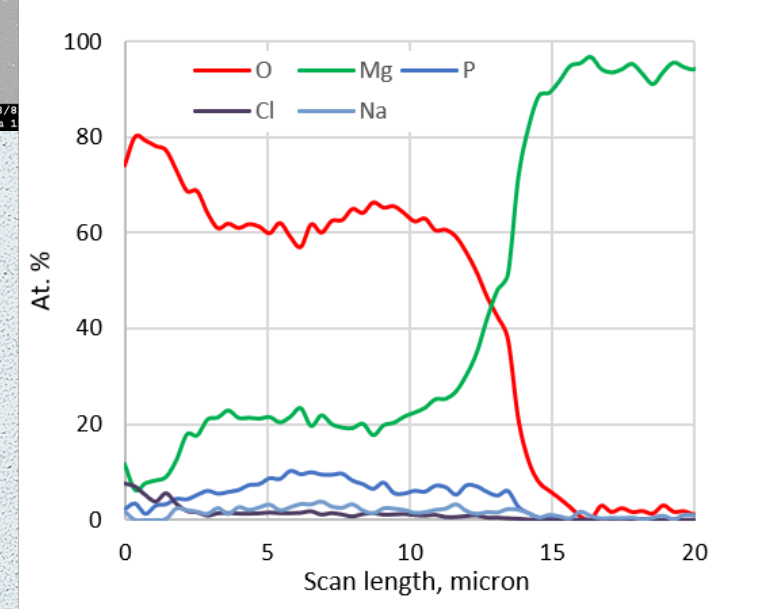
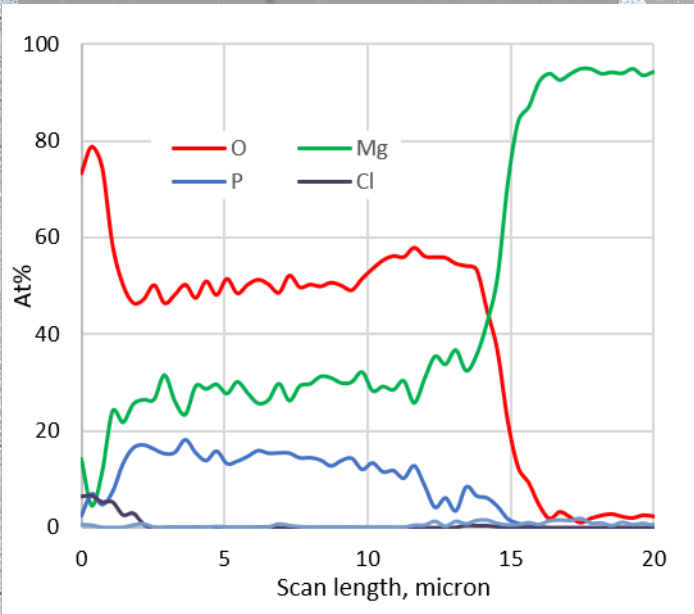
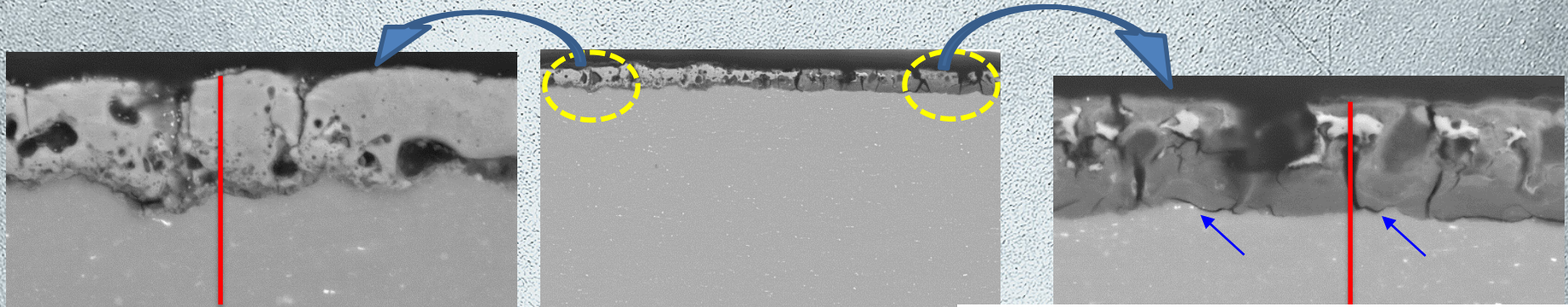


AZ31 + HPEC

No apparent change in  
the protective layer



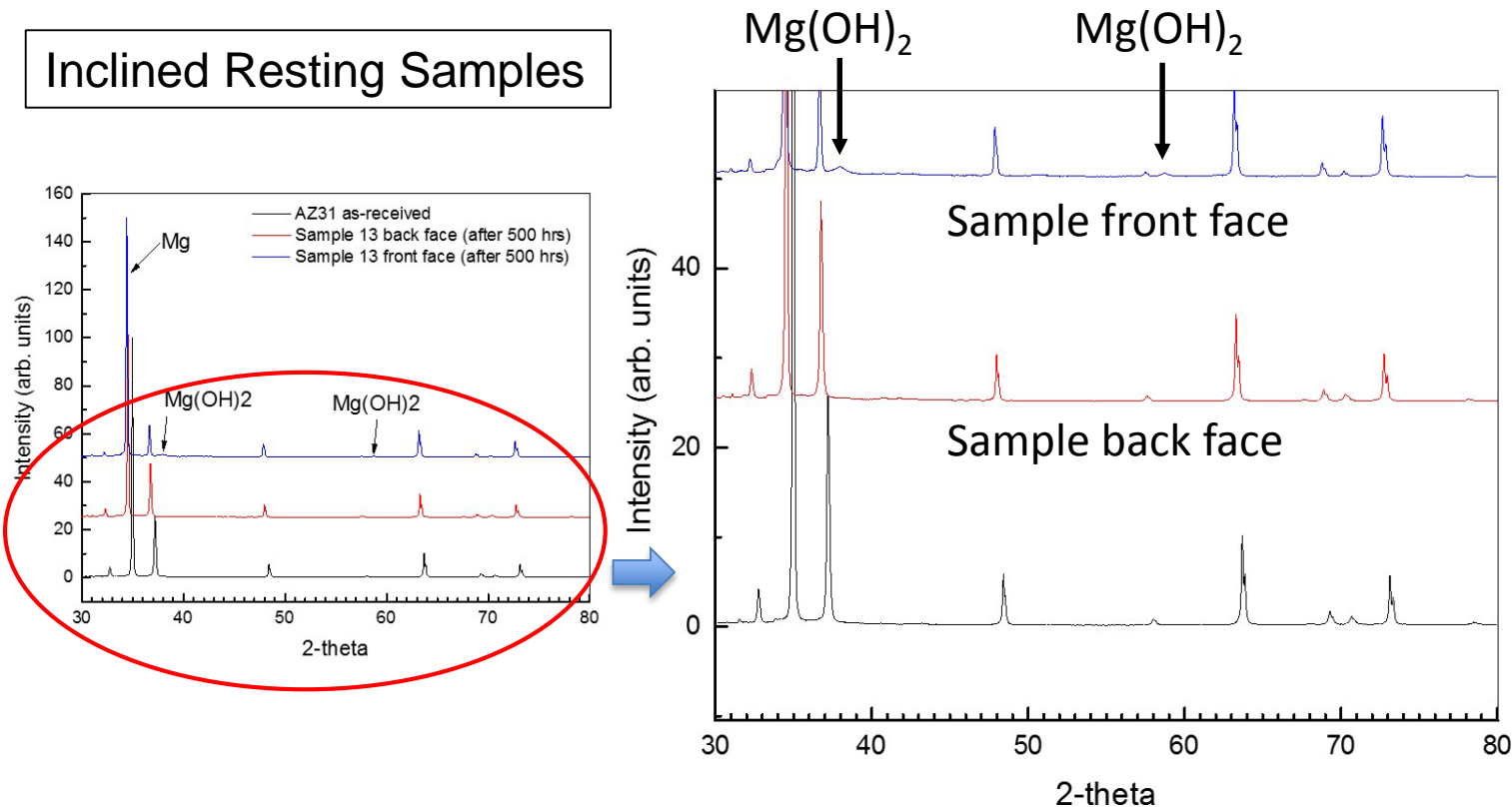
# AZ31 + HP coupons (SEM + EDS analysis) , $t = 850$ h



**Formation of Mg-hydroxide on areas where HP-layer got removed, confirmed by EDS and XRD. Cracks noted at the metal IF, shown by arrows**

# X-ray Diffraction of Corrosion Products

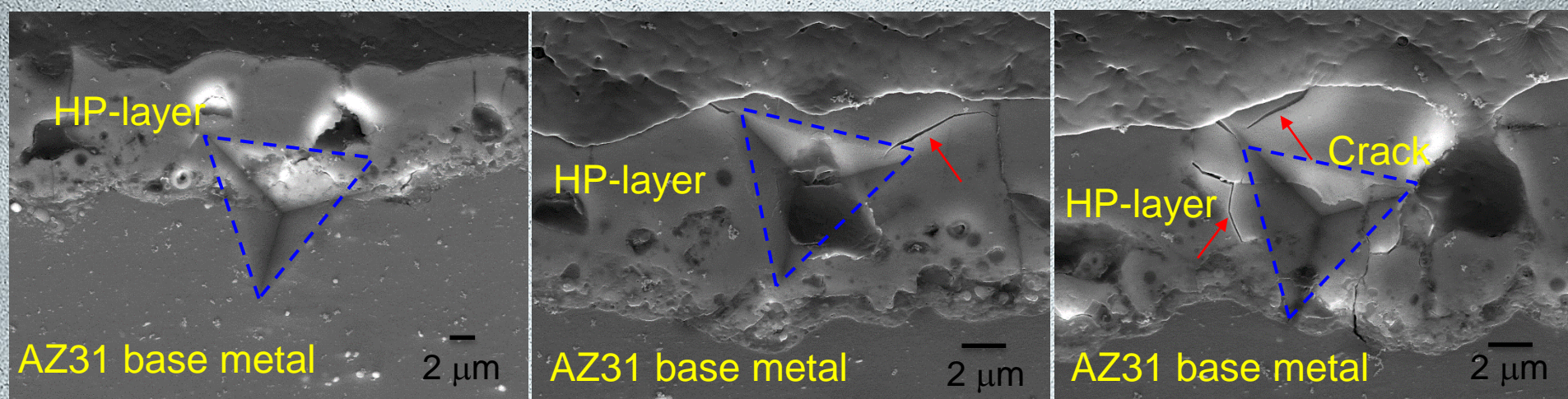
## Inclined Resting Samples



- XRD analysis confirmed the presence of  $\text{Mg(OH)}_2$  as the corrosion product, on the front face



# Indentation along coating/base metal to check coating integrity, AZ31 + HP Coupons



- Nano-indentation along the HP-layer/metal interface and inside the HP-layer carried out (0.1-1 N, Berkovich indenter)
- Signs of interfacial failure/coating delamination at HP-layer/Mg-base metal interface is not evident.
- A few cracks can be noted within the coating, but not extensive